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# Zero Power Buoyancy Control for Distributed Autonomous Sensor Networks Conducted During Crimson Viper 2010 Field Experiment

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14. ABSTRACT The Office of Naval Research (ONR)/Naval Research Laboratory (NRL) Reserve Program (Program 38) was tasked to conduct an experiment on ONR and NRL technologies that were incorporated into the U.S. Marine Corps Forces Pacific (MARFORPAC) Experimentation Center (MEC) Crimson Viper 2010 (CV10) Field Experiment. This specific experiment addresses the Zero Power Ballast Control (ZPBC) for Distributed Autonomous Sensor Networks. The experiment was conducted by ONR Program 38 officers for the NRL Materials Science & Component Technology Directorate, Code 6115. The purpose of the ZPBC for Distributed Autonomous Sensor Networks experiment is to evaluate the prototype's maturity and utility for field deployments and provide recommendations for future improvements and testing. The ZPBC prototype is a technology developed by NRL Code 6115 which relies on microbial energy harvesting developments with the ultimate goal of producing simple, small, power-efficient data harvesting nodes with variable buoyancy, enabling unsupervised underwater sensing with subsequent surfacing and reporting capabilities. These sensors could be designed to detect and classify, rise to the surface, report using radio frequency (RF) or other communication, then re-submerge and continue monitoring operations. The systems are based on microbial metabolism with variable ballasting offered by biological H <sub>2</sub> production. Current prototypes offer the possibility of one to ten year deployments. This technology was assessed during CV09 and CV10 by ONR Program 38 officers and tests were conducted to determine how well, under what circumstances, and under what conditions the ZPBC prototype system performed in the field.					
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## EXECUTIVE SUMMARY

The Office of Naval Research (ONR)/Naval Research Laboratory (NRL) Reserve Program, (Program 38) was tasked to conduct an experiment on ONR and NRL technologies that were incorporated into the U.S. Marine Corps Forces Pacific (MARFORPAC) Experimentation Center (MEC) Crimson Viper 2010 (CV10) Field Experiment. This specific experiment addresses the Zero Power Ballast Control (ZPBC) for distributed Autonomous Sensor Networks. The experiment was conducted by ONR Program 38 officers for the NRL Materials Science & Component Technology Directorate, Code 6115, and the Ocean and Atmospheric Science and Technology Directorate, Code 7130. The purpose of the ZPBC for Distributed Autonomous Sensor Networks experiment is to evaluate the prototype's maturity and utility for field deployments and provide recommendations for future improvements and testing.

The ZPBC prototype is a technology developed by NRL Code 6115 which relies on microbial energy harvesting developments with the ultimate goal of producing simple, small, power-efficient data harvesting nodes with variable buoyancy, enabling unsupervised underwater sensing with subsequent surfacing and reporting capabilities. These sensors could be designed to detect and classify, rise to the surface, report using radio frequency (RF) or other communication, then re-submerge and continue monitoring operations. The systems are based on microbial metabolism with variable ballasting offered by biological H<sub>2</sub> production. Current prototypes offer the possibility of one to ten year deployments. This technology was assessed during CV09 and CV10 by ONR Program 38 officers and the following tests were conducted to determine how well, under what circumstances, and under what conditions the ZPBC prototype system performed in the field. Device effectiveness and performance measures were evaluated in terms of:

- Device surfacing and re-submergence at controlled frequency
- Reliability, robustness and longevity
- Temperature versus gas production
- Remote sensing data collection in support of future sensor selection/incorporation for Maritime Domain Awareness assessments.

ZPBC trials were successful in many ways. The device surfaced and submerged as designed via hydrogen gas produced from the microbial inoculum and growth medium. The rise and fall of the device was supported by pressure and temperature sensor data and direct observation. The bacterial fuel source (inoculated gas production vessel) was attached to the two ZPBC devices which were then deployed *in situ* off a military pier in Sattahip, Thailand, held in place by mooring lines for seven days.

Based on observation, the device can surface and submerge under microbial gas-generated power. Data were collected for pressure and temperature during the entire deployment. One device was set to surface every 9 hours, the other every 12 hours. Sufficient gas was generated to allow surfacing in the first instance. The second ZPBC initially had difficulties re-

sinking. Additional weights were added which most likely prevented the device from creating enough gas to surface. Ultimately, sensors (e.g., acoustic, magnetic) attached to the ZPBC may detect and classify, rise to the surface, report using RF or other communication, then re-submerge and continue monitoring operations.

All four experiment Measures of Effectiveness (MOEs) were completed as the ZPBC device generated gas in sufficient quantity to produce buoyancy, float to the surface, vent buoyancy gas, and sink under varying natural and man-made conditions. Further testing, evaluation and prototyping are required before deployment would be fruitful in an operational setting. Therefore, this technology would not be ready for the next COBRA GOLD exercise in early 2011. Although in an early stage of development, the ZPBC does have the potential for future military application. Use of this technology most likely would be in littoral areas, but depending on bacterial performance at increased depth, blue water applications may be considered.

The following key recommendations should be considered for future ZPBC development:

- Attach additional sensors to collect data of interest (e.g., salinity, temperature, in-water optics, geo-location, etc).
- Include a RF communications link.
- Use hydrogen gas production to generate electricity via a fuel cell in addition to ballast control.
- Arrange for increased depth and analyze microbial performance under higher pressure and lower temperature.
- Test blue water application (i.e., at increased depths).
- Investigate methods and structure design to mitigate device fouling from barnacles, sea life, and general corrosion.
- Test device in an un-tethered environment.
- The watertight integrity and overall physical design were satisfactory. However, improvements to the casing and sensor/fuel cell housing for more physically robust handling and deployment are warranted.

## **PURPOSE**

The Office of Naval Research (ONR)/Naval Research Laboratory (NRL) Reserve Program, “Program 38,” was tasked to conduct a series of experiments on a select set of ONR and NRL technologies during the Crimson Viper 2010 (CV10) field experiment. One of these technologies was a field deployed, zero-power ballast control system that could be designed to operate autonomously for long periods of time (years). It required special designs to maximize its operational lifetime and is called the “Zero Power Ballast Control (ZPBC) for Distributed Autonomous Sensor Networks.”

This technology was developed by the NRL Bioenergy and Biofabrication Section, Code 6115, in collaboration with the Physical Acoustics Branch, Code 7130. Because this technology

is at the 6.2 funded development stage, the purpose of this experiment was to provide recommendations for future improvements and testing, as well as to conduct basic research as the prototype is not warfighter ready. The device is substantially modified from the one tested at CV09. The sponsor requested a ballast “holding chamber” arrangement so that the device can be “triggered” to surface from a remote command in addition to regular intervals. This modification adds additional power requirements which, for the current prototype, will be battery-based. Future modifications will, as in the original design criteria, utilize hydrogen gas produced by bacteria for fuel-cell-based energy harvesting and “self” powering.

## ASSESSMENT METHODOLOGY

### *General*

ONR Program 38 officers conducted the ZPBC Distributed Autonomous Sensor Networks experiment as part of the CV10 Field Experiment at the Sattahip Royal Thai Navy and Marine Corps Base in Chonburi Province, Thailand from 10 to 25 July 2010. CV10 represents testing for the Program's second prototype device. The assessment focused on the buoyancy ballast capability of the device. Although this technology is not ready for a formal Military Utility Assessment (MUA), the systems were tested in CV10 by ONR/NRL Reserve Program 38 officers in accordance with the Program 38 MUA Process Manual. The ZPBC experiment was conducted to address the Critical Operational Issues described in the following section.

### *Critical Operational Issues*

Critical Operational Issues (COIs) are questions, that when answered through the CV10 experimentation process, determine if the technologies demonstrate sufficient military utility to warrant further investigation. The COIs must be answered using verifiable data, sound analysis, and clear judgment. Each COI is intended to be answered over the course of the experiment by exploring Measures of Effectiveness (MOEs) and Measures of Performance (MOPs). During CV10, all the ZPBC COI measures were planned to be addressed, but some questions were not fully answered due to the scope of the experiment and assigned manning. Table 1 lists the set of COIs and their corresponding sub-elements identified by the ZPBC assessment team.

***Table 1: Critical Operational Issues and Measures***

<b><i>MOP 1</i></b>	<b><i>Device gas generation</i></b>	<b><i>Does the device generate gas in sufficient quantities and sufficient speed to produce calculated buoyancy?</i></b>
<b><i>MOP 2</i></b>	<b><i>Device flotation</i></b>	<b><i>Does the device float to the surface within calculated time-points? What are the impacts of temperature, salinity, density, depth and thermocline presence to operation?</i></b>
<b><i>MOP 3</i></b>	<b><i>Device sinking</i></b>	<b><i>Does the buoyancy chamber camber properly under varying conditions? what level of sea-states, wind-strains, shipping activities impacts performance?</i></b>

<i>MOP 4</i>	<i>Device longevity</i>	<i>Does the device produce gas for the calculated timeframe? Does temperature or density impact gas production longevity?</i>
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### ***Crimson Viper Overview***

Crimson Viper is a Thai-US technology collaboration experimentation event jointly sponsored by the US Pacific Command (USPACOM) and the Royal Thai Defense Science and Technology Department (DSTD). The U.S. Marine Corps Forces Pacific (MARFORPAC) Experimentation Center (MEC), under the leadership of its Director, Mr. Shujie Chang, acts as the Thailand Science and Technology (S&T) executive agent for USPACOM. The Crimson Viper international field experimentation team, consisting of over 60 personnel from various organizations, executed CV10 from 12-25 July 2010 at the Sattahip Royal Thai Navy and Marine Corps Base in Chonburi Province, Thailand. The primary objectives of Crimson Viper are to experiment with candidate technologies in a field environment to:

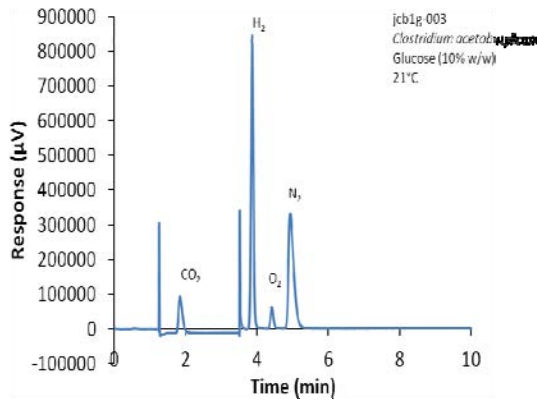
- Support S&T collaboration in support of the USPACOM Theater Security Cooperation Program
- Promote interoperability between the Royal Thai Armed Forces (RTArF) and USPACOM requirements
- Assess candidate technologies and provide assessment feedback to the S&T community
- Confirm technology maturity prior to introducing into military exercises (e.g., Cobra Gold, Balikatan, Talisman Saber, etc.).
- CV10 results will help steer project development and also determine which technologies are ready for assessment in the Cobra Gold 2011 and other USPACOM exercises, with the ultimate goal being transition of the systems to operational forces.

### **SYSTEM DESCRIPTION**

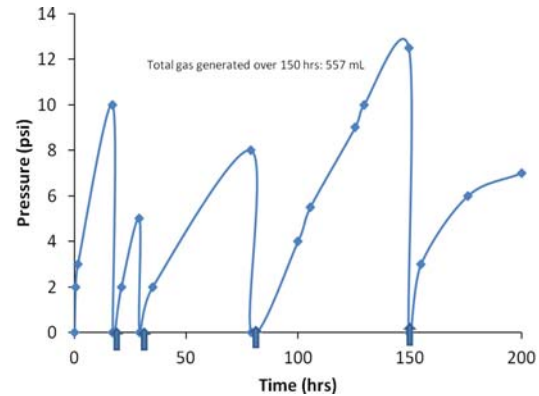
During CV09, the first generation ZPBC was tested. Sufficient gas was produced to provide positive buoyancy and allow the device to surface autonomously. These tests offered ideas for enhancements and identified areas of improvement for the device. These lessons learned and refocus efforts driven by the sponsor have led the development team to alter the design criteria for the second generation ZPBC. One of the principal design changes involves moving from an autonomous surfacing interval to surfacing on command (given an “outside” stimulus). Currently, the prototype has been designed to trigger surfacing on a timer-based command signal (the communications hardware is either currently available or under concurrent development). CV10 focus involved chamber and valve design evaluation, microbial inoculation and growth support media changes, and in-water performance evaluations.

A key new feature of the current prototype (relative to the CV09 system) is that the current system is able to generate hydrogen gas at pressures greater than 30 pounds per square inch (psi). The prototype relies on growth from *Clostridium acetobutylicum*, a hydrogen-producing bacteria able to consume carbohydrate food sources. While the system is not limited to

solely *Clostridium* spp., the currently fielded device works with an inoculated *C. acetobutylicum* strain. The organism is non-pathogenic and safe for handling and disposal (air exposure



**Illustration 1: Gas composition**



**Illustration 2: Gas generation over time**

incapacitates this obligate anaerobe). The prototype is designed to generate significant renewable pressures from gases produced by microorganisms for either fuel delivery or ballast generation. There are important military and commercial applications for such a system which would require limited re-fueling. The system will be used ultimately to extend operational autonomous sensor duration or unmanned underwater vehicles (UUV) and also could be used for portable power supplies. Re-pressurizing gas tanks with bacteria will eliminate the need to transport tanks to external fueling stations, generate gaseous fuels on-site using biomass, or to provide ballast for long-duration aquatic sensors, communication relays, and buoys. Generating pressure via bacteria will enable the production of fuels and ballast separate from fossil fuel derived methods and processes.

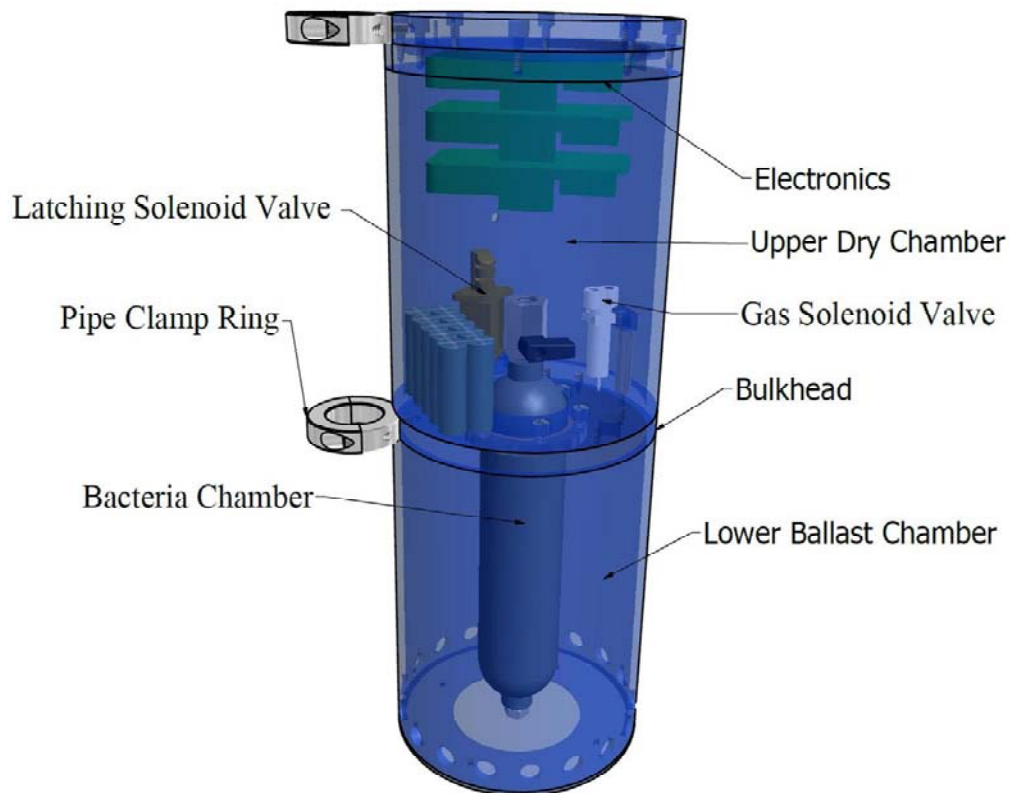
The initial change in microbial growth substrate medium is designed to “slow down” gas production but allow organisms to build up considerable pressure under growth. At 21°C, with a growth media containing 35% glucose, 35 PSI pressure was developed in the gas holding tank associated with the growing organisms. After venting, the microbial culture was able to re-pressurize the vessel repeatedly. This has led to the chamber redesign such that gas (>60% hydrogen, Illustration 1) can be “stored” in a pressurized container and be remotely (or for CV10 experiments on-timer) stimulated to vent into a ballast chamber in order to make the device surface (Illustration 2).

The current device is composed of two chambers, one “dry” which contains the electronics, valves, solenoids, and (in the case of CV10 prototype) timers. The lower chamber contains the growth chamber (which becomes pressurized while bacteria are growing). Clamp rings are fitted on the current CV10 prototype to allow the ZPBC unit to remain upright in the water column – held in place horizontally by a suspended mooring line (Illustration 3). Ultimately, the design goals are:



1. The device should automatically rise to the surface along a tether, pause at the top and then sink again. It should be able to perform this several times per day.
2. The device should resist corrosion, clogging, and the pressure of 10 meters of sea water. It should not sink into the sand or sediment of the ocean floor.
3. The gas produced by the bacteria is hydrogen. Special material will need to be utilized to minimize the leakage of hydrogen.
4. The bacterial chamber should be filled with agar in an anaerobic environment. The chamber should also permit the injection of the bacteria into the agar with a syringe and needle. The injection should be possible in the field while maintaining the anaerobic environment.
5. The valve system should use minimal power, permitting reduced battery size and increased operating time.

***Illustration 3: ZPBC Prototype Device***

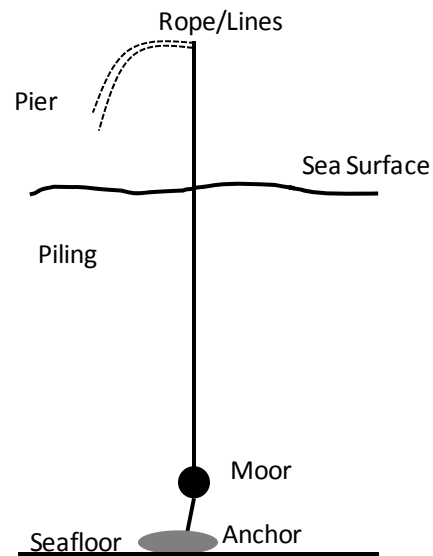


The device is assembled on-site and has settings for duration between cycling (how often it comes to the surface), how long it should stay at the surface, and how long the valve is open to allow gas to fill the lower chamber. Much of this is to be tested at CV10 in order to assess the device's performance and future development needs.

## Test Event Measures

The ZPBC system was tested for operation in a real-world location. The test involved several sequential steps. Initially, the devices were inoculated with *Clostridium acetobutylicum* as soon as possible during the exercise to allow the organisms to begin growing and producing hydrogen gas. Two inoculum schemes were used. In the first, lyophilized organisms were resuspended in fresh liquid medium, then immediately used to inoculate the ZPBC agar chamber. In the second, the liquid medium with resuspended cells was allowed to incubate for 48 hours in order to increase cell abundance. Then the liquid medium was used to inoculate the ZPBC agar chamber. An agar growth medium (containing ~75% agar – substantially higher than in “normal” growth media) was used in the bacteria chamber.

While organisms were growing and increasing biomass (and thus gas production), the CV10 ZPBC team assembled and tested the remainder of the ZPBC device. The pressure chamber and release solenoids were tested in a controlled environment (pool) in order to adjust ballast and ensure proper electronic actuation (for the solenoid valves). The chamber was pressurized using compressed air to test ballasting, disposition in the water column, sensors, and data recording system. The first operational day, the ZPBC team installed the mooring system on the pier. The mooring system consisted of an anchor or weight placed on the sea bottom. The anchor was fitted with a line which was attached tautly to the davit system (Illustration. 4). This configuration was chosen to allow the ZPBC to be attached to the rope and move only vertically in the water column. The electronics (inducing a change in valve positions at regular intervals) were activated after the devices were affixed to the mooring lines. The temperature and pressure probes were affixed and activated, and the ZPBC system was then placed unattended in the water column. Once deployed, the ZPBC was checked daily to make sure no fouling occurred, that the lines/ropes were holding and taut. Daily status was logged and sensors were removed data downloaded, and replaced at regular intervals during the tests.



**Illustration 4: Davit-mooring for ZPBC.**

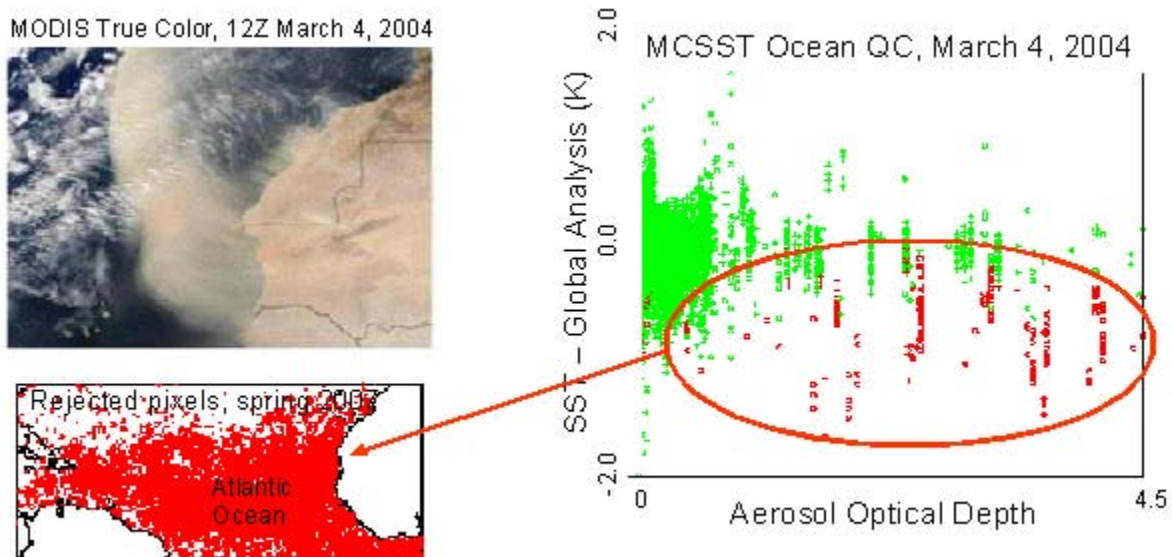
## Additional Measures

The ZPBC's ultimate purpose is to provide persistent surveillance in operational environments. Two examples of relevant tactical data are sea surface temperature and in-water optical properties. These measurements are critical to operational commanders as they can be used to ground-truth remote sensed data (which has spatial and temporal resolution to encompass the entire scope of the operational theater). These data are critical to obtain in the operational environment because satellite returns are greatly compromised by variations in the atmosphere – particularly aerosol-induced scattering. For instance, water-leaving radiance cannot be accurately

calculated from satellite data using residual radiance if heavy aerosol loading occurs. These issues are troublesome for current models – of particular concern, the Automated Optical Processing System (AOPS) used by the Naval Oceanographic Office (NAVOCEANO) for 70 plus tactical areas of interest. The ZPBC will ultimately be used in providing in-water optical data to enhance models for underwater swimmer visibility, laser penetration depths, diver and target vulnerability assessments, electro-optical system performance predictions, and refining numerical models.

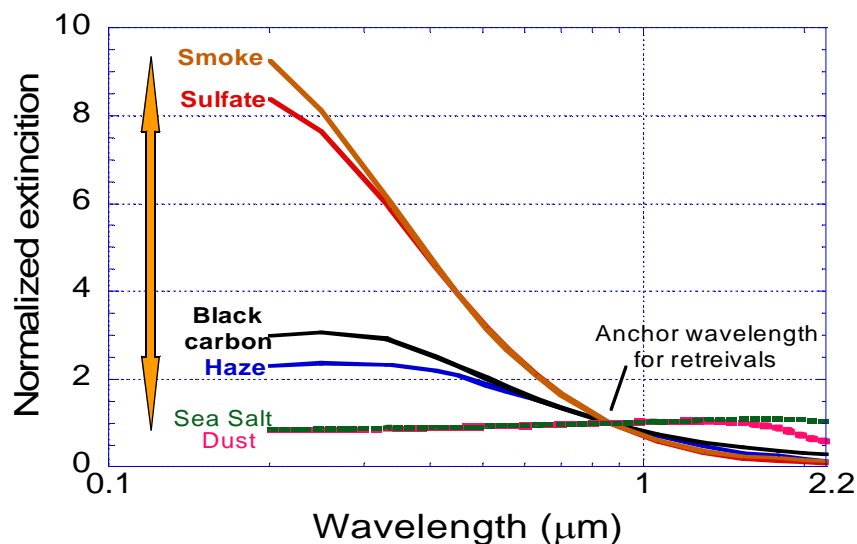
Sea surface temperature is remotely sensed using satellite infrared channels. These channels are “cold-impacted” by dust clouds prevalent in many coastal regions, causing many rejected pixels, and thus inaccurate data for operational environment data products. Data products relying on accurate sea surface temperature measurements (or estimates) involve regional and global weather forecasting, nowcasting, sound speed profiles and current profiles for tactical support (Illustration 5).

The ZPBC team performed several ancillary experiments in order to gather in-water optical data (planned to be used to ground-truth contemporaneous HICO returns) and gather aerosol samples for subsequent analysis at NRL. At regular intervals, a hand-held hyperspectral sensor as to be used to collect near-water optical data returns. Pier locations were used and timed to coincide most closely with HICO (hyperspectral satellite) overpasses was taken into account. The remote sensing data will be processed at NRL subsequent to this report's publication. Additionally, the sea surface temperature taken by the temperature probe attached to the ZPBC will be used to ground-truth satellite-based SST estimates for the region (subsequent to this report's publication). Finally, small battery-operated pumps were used to collect aerosol particles over 24 hour deployments. These filtrations were performed five times during CV10 at three



***Illustration5: Rejected pixels due to dust***

separate locations in order to obtain temporal as well as spatial particle information. The pre-



**Illustration 3: Extinction due to different optical interference**

tared filters were returned to NRL for further processing which includes gravimetric measurement, extraction and analysis by gas chromatography-combustion via isotope ratio mass spectrometry. The aerosol material will be assayed for “chemical” nature so that optical extinction estimates can be made for ground-truthing (*c.f.* Illustration 6).

## TEST METHODOLOGY

### *Measures: COIs / MOEs / MOPs*

The ZPBC COIs and accompanying MOEs and MOPs are detailed in the following paragraphs. A second-generation prototype was used during CV10. Conceptually, gas generation “inflates” the device and causes it to surface. This was demonstrated with initial prototypes. Field/operational conditions provided both foreseen and unforeseen complications. We anticipated performing several tests. Two devices were provided by the principal investigators (PIs) so two separate moorings were placed and two different cycling times were programmed in the devices. While estimates have been made (*c.f.* Illustration 1), it was unknown how rapidly the microbes would produce gas at the temperature/pressure at the field site. This uncertainty affected the speed and frequency with which the ZPBC will surface and “report.” A watch was set to observe the system’s performance (from the pier). As a backup, the test team fitted a data recording system on the device to record water depth at 1.5 second intervals. The team also recorded each surfacing event visually.

Two different inoculation strategies were used. One chamber was inoculated directly from a re-suspended lyophilized culture. The other was inoculated from a 48-hour culture produced by re-suspending lyophilized cells, then allowing them to grow for 48 hours. Subsequent testing included the microbial culture as the gas-producing agent. These tests spanned the entire CV10 field campaign duration. The following indices of performance were observed over the course of CV10.

- Each surfacing event
- Time interval(s) between surfacing events

- Direct observations were made and a recording pressure sensor was employed to allow reconstruction of all vertical water column movements.
- Temperature.

### ***Test Apparatus***

The test apparatus is described in the System Description section.

### ***Test Assumptions***

The ZPBC operational assessment was designed to capture feedback based upon system deployment during the assessment period. The assessment design and its anticipated validity are predicated on the following assumptions:

- The warfighters responsible for ZPBC maintenance and operations during the operational assessment were fully trained prior to initiation of data collection.
- The ZPBC device was deployed during the assessment to provide data collection with the system executing a representative mission profile expected during operational deployment.

### ***Test Limitations***

The CV10 experimentation venue did not replicate real-world conditions or environments that NRL anticipated within their area of operations. The following artificialities limited the scope of the assessment:

- Weather/Terrain: Climatic conditions reflected conditions in the anticipated CV10 Area of Operations (AOR) – although envisioned deployments may be in deeper waterways.
- Time/Duty Cycles: The duration of the CV10 field experiment limits reliability and availability assessments for long-term ZPBC deployments. Operational constraints for setting watch at the pier did not allow for around the clock observation.
- Transition Level: The current 6.2 prototype is designed to test proof of concept. Warfighter evaluation is premature at this time. Real world testing is the current objective.

### ***Test Event Design***

During the assessment, the Program 38 Assessment Team exercised the prototype in an operational environment providing the data for evaluation. The assessment took place from 12 to 25 July 2010 at the Sattahip Royal Thai Navy and Marine Corps Base in Chonburi Province, Thailand.

### ***Test Event Variables (Factors and Conditions)***

Prototype ZPBC evaluation included the factors and conditions presented in Table 2, including identification of which factors were varied, how the factors were controlled, and under what operational conditions. Control is specified as systematically varied, tactically varied, held constant, or uncontrolled.

**Table 2: ZPBC Factors and Conditions**

Factors	Control	Conditions
Temperature	Systematically varied*	Natural water column(s)
Tidal movement	Systematically varied*	Natural water column(s)
Varying temperature	Systematically varied*	Thermocline(s)
System operating status	Uncontrolled	Fully operational, non-operational, degraded performance.
Weather	Uncontrolled	Rain, wind, dry, cold

\*As provided by daily tide/wind/current patterns

## TEST RESULTS

Initial setup at CV10 was led by inoculating growth media with lyophilized *Clostridium acetobutylicum* (Illustration 7). Two growth-inducing strategies were undertaken. First, one set



**Illustration 7: Inoculating microbial fuel cells**



**Illustration 8: Tethering setup**

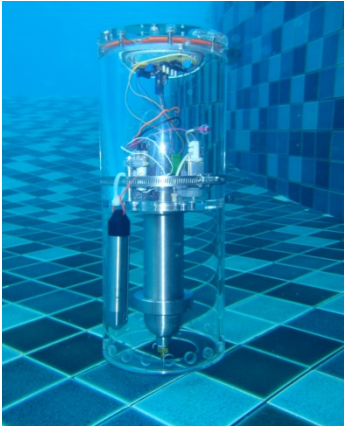
of lyophilized organisms was re-suspended and immediately used to inoculate the pressure chamber (Illustration 3 - The growth chamber is the stainless “tube” with green valve). Another set of lyophilized cells was re-suspended, then injected into liquid growth medium in order to increase titer before inoculating the pressure chamber.

After inoculation, pier operations were undertaken to prepare for ZPBC deployment. Two platforms were used, one for each device. An anchor was secured on the bottom to which a rope was affixed. A series of knots was



tied roughly 0.5 m from the anchor as a stop (to keep the ZPBC from sinking all the way to the anchor). Then, the ropes were secured taught to the pier platform to create a vertical tether for each ZPBC (Illustration 8).

During the 48 hours of incubation time needed to obtain an active, gas-producing culture, the CV10 team worked on determining the correct ballast needed to provide each ZPBC with



***Illustration9: ZPBC on bottom***



***Illustration10: Adjusting ZPBC buoyancy***

optimal buoyancy (slightly negative). The devices were brought to a pool for these tests. A scale was not available, but enough ballast was added in the pool environment to just sink each device (Illustrations 9-10).

After 48 hours of pre-incubation, the second ZPBC pressure chamber was inoculated with the starter culture, and each ZPBC buoy was assembled, timers set, and moved to the pier location. Buoyancy additions for the ambient salinity found on site were made along with in-water adjustments so that each device was just slightly negatively buoyant before affixing to the support rope. Each device was then affixed to the support line and allowed to sink on the line. After this evolution, optics and meteorological data were taken from the pier (wind, direction, relative humidity, total solar irradiance, hyperspectral reflectance, and particle collection). At regular intervals (every 24 to 48 hours), the ZBPC buoys were brought to the surface, sensors removed and data downloaded, then returned to the water. The proximal ZPBC (set for 12 hours) appeared to be staying at the surface indefinitely. Three days into the experiment, an addition 1.5 oz of weight was added. At day 5, an additional 1.5 oz was added as the device was still floating long after the sinking “directive” was given.

Based on observation, the device can surface and submerge under microbial gas-generated power (Illustrations 11-12). Sensors (*e.g.*, acoustic, magnetic) attached to the ZPBC could be used to detect and classify, monitor the rise to the surface, report using RF or other communication, then re-submerge and continue monitoring operations.

All of the MOEs were completed as the ZPBC device generated sufficient gas (Table 3).

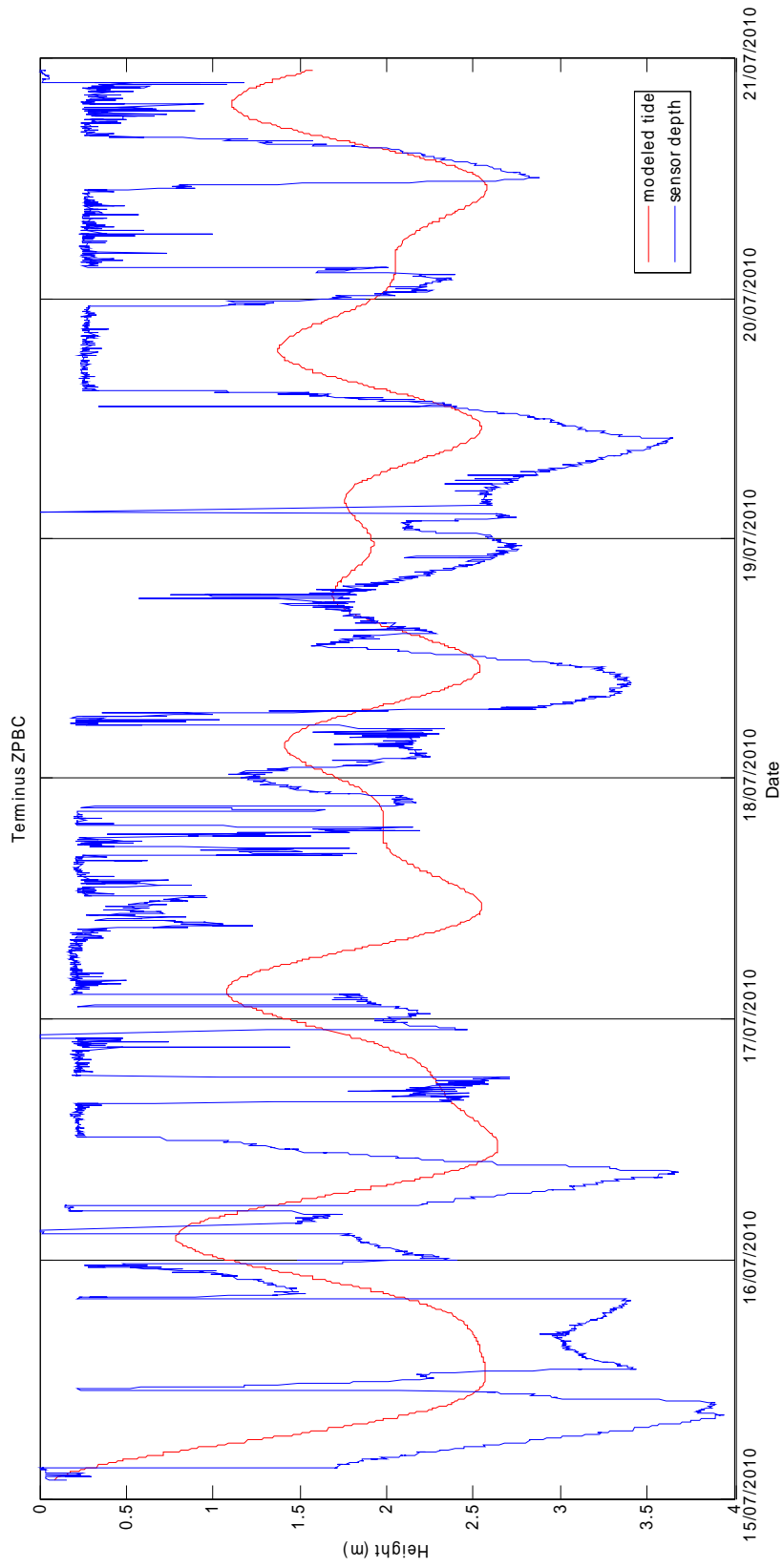
Four MOPs were partially completed as the ZPBC device generated gas in sufficient quantity to produce buoyancy, floated to the surface, vented buoyancy gas, and sank under varying natural and man-made conditions. Ongoing data analysis will allow a refined understanding of system performance.

**Table 3: ZPBC MOP Results**

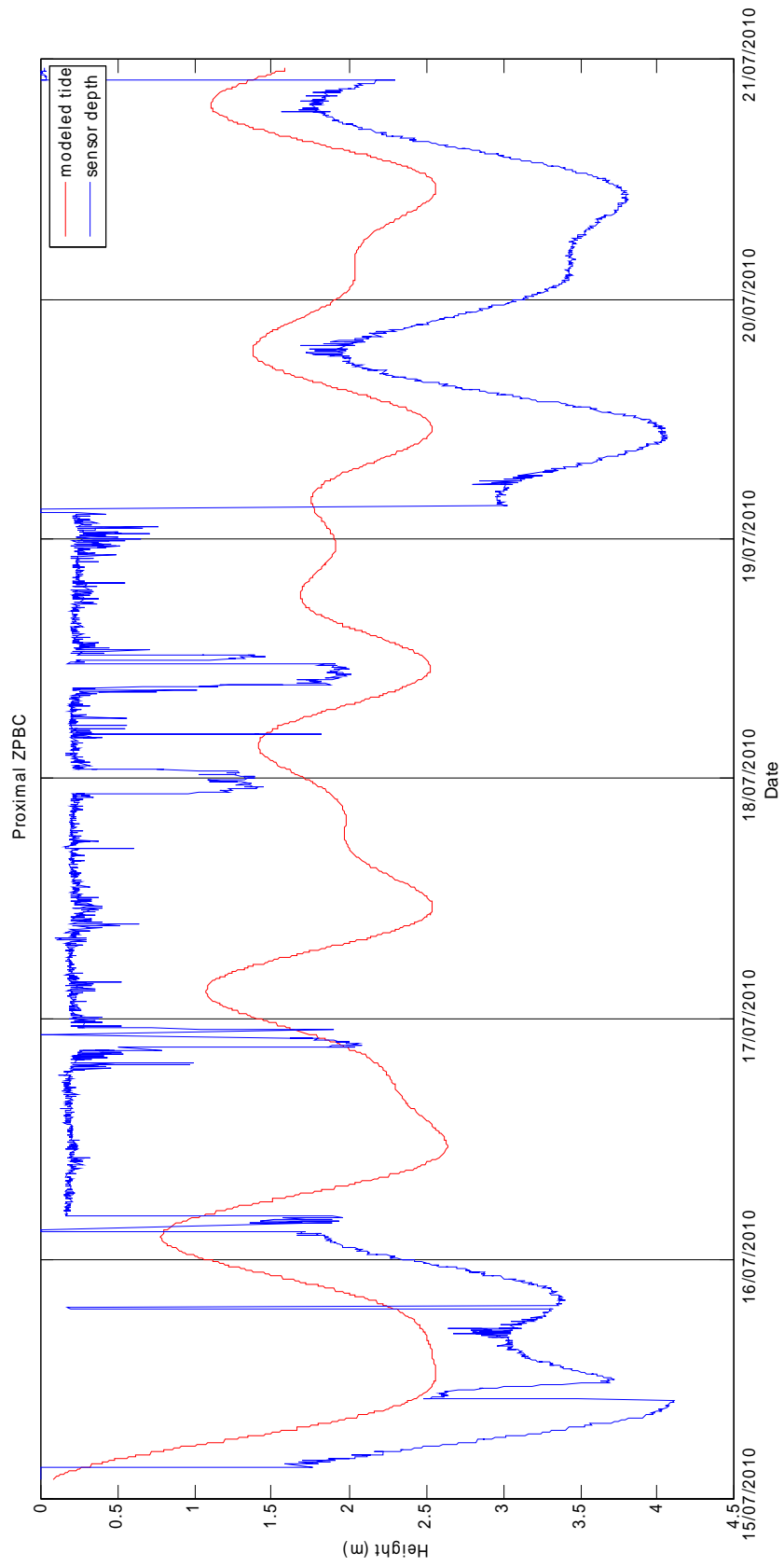
<b>MOP#</b>	<b>MOP Title</b>	<b>MOP</b>	<b>Result</b>
<i>MOP 1</i>	<i>Device gas generation</i>	<i>Does the device generate gas in sufficient quantities and sufficient speed to produce calculated buoyancy?</i>	<i>Devices were observed surfacing multiple times. MOP-1 confirmed</i>
<i>MOP 2</i>	<i>Device flotation</i>	<i>Does the device float to the surface within calculated time-points? What are the impacts of temperature, salinity, density, depth and thermocline presence to operation?</i>	<i>Devices surfaced within 24 hours of deployment. Difficult to assess if temperature variation(s) impacted gas production</i>
<i>MOP 3</i>	<i>Device sinking</i>	<i>Does the buoyancy chamber camber properly under varying conditions? What level of sea-states, wind-strains, shipping activities impacts performance?</i>	<i>Devices surfaced and submerged under variable conditions (tides, wind field). Unable to directly test other variables.</i>
<i>MOP 4</i>	<i>Device longevity</i>	<i>Does the device produce gas for the calculated timeframe? Does temperature or density impact gas production longevity?</i>	<i>Devices produced gas for the entire 8 day deployment. It was producing gas when recovered.</i>



***Illustration 11: Terminus ZPBC performance and tidal model***



***Illustration 12: Proximal ZPBC performance and tide model***



## CONCLUSIONS AND RECOMMENDATIONS

With all MOPs completed, this field experiment was considered successful and the next generation device should be included in CV11. Data collected demonstrated that the ZPBC successfully surfaced using microbial gas generation and re-submerged as designed. Additionally, the device can surface “on-demand” using the configurable timer. Military utility and scientific applications include use in Intelligence Surveillance and Reconnaissance (ISR), Anti-Submarine Warfare (ASW), Mine Warfare (MIW), Naval Special Warfare (NSW), and Meteorology and Oceanography (METOC).

Remote sensing reflectance was measured successfully using an hyperspectral handheld unit. Water-leaving radiance and sun radiance were measured. These measurements may be used in conjunction with ZPBC to ground truth satellite sensing. CV10 measurements will be fed into existing NAVOCEANO and NRL models which immediately assist current products and drive future ZPBC sensor choices and development.

In the future, the device would be able to monitor ocean temperature for a longer term than other mechanisms such as the Expendable Bathythermograph (XBT). With a stay time ranging from weeks to months and eventually years, the ZPBC provides input for robust modeling of ocean temperatures and other parameters.

Future recommendations for ZPBC improvement, prototyping and deployment scenarios:

- Attach additional sensors to collect data of interest (*e.g.*, salinity, geo-referencing, optical properties, etc).
- Include a RF communications link.
- Use hydrogen gas production to generate electricity via a fuel cell.
- Arrange for increased depth and analyze microbial performance under higher pressure and lower temperature.
- Test blue water application for the ZPBC technology (increased depths and pressures).
- Investigate methods and structure design to mitigate device fouling from barnacles, sea life, or general corrosion.
- Test device in an un-tethered environment.
- Continue collecting measurements for remote sensing application to ground truth satellite sensing data with in-water collected measurements.
- If feasible and practical, coordinate reflectance and radiance measurements with hyperspectral satellite overflights.
- The watertight integrity and overall physical design were satisfactory. However, improvements to the casing and sensor/fuel cell housing for more physically robust handling and deployment are warranted.
- Deploying multiple ZPBC devices enhanced data gathering and provided excellent system backup. Continue to employ multiple devices in field experiments.
- Secure similar pier and waterside accommodations for CV11.

Lessons were learned and challenges remain for the ZPBC technology to address these issues:

- Gas venting did not always occur as configured. Gas vents to water, which may be at a pressure that slowed or prevented venting. Compression properties at depth of the hydrogen gas must be analyzed to model system function.
- Data show that system remained at surface longer than programmed in some cases, perhaps due to gas venting difficulties. Essentially, although successful, the gas venting system requires redesign to ensure system surfaces and submerges as programmed taking into account environmental conditions.
- Other influences that may affect gas venting or designed operation include the tether line, tube fouling, tides, current, and wind.
- Additional performance modeling and analysis are required to account for environmental factors such as temperature, depth, and salinity.
- Predetermine ballast needed for slightly negative buoyancy and have the ability to change ballast on site.

Much progress has been made for the ZPBC technology. A second generation prototype proved more robust, more capable and had greater deployability in the operational environment provided by CV10. The sponsor-driven enhancement of controllable surfacing allowed the ZPBC to surface at a timed interval. While this feature increased the possible tactical flexibility, it may not allow for maximum gas buildup and may impact the device's ability to surface on command. While the ZPBC devices did surface at the set intervals, re-submergence was hampered by inconsistent venting. The NRL team is already seeking means to make venting more robust by increasing the vent tube diameter. The device's ultimate autonomy is still hampered by the need to tether it during testing. Continued prototyping could include geo-referencing capabilities so that the device could be untethered in future tests.



## APPENDIX A: Acronyms

AOPS	Automated Optical Processing System
AOR	Area of Responsibility
ASD	Official name of company (ASD Inc.). Analytical Spectral Devices, Inc. (before June 2007)
ASW	Antisubmarine Warfare
CV	Crimson Viper
CV09	Crimson Viper 2009
CV10	Crimson Viper 2010
CV11	Crimson Viper 2011
COI	Critical Operational Issue
DSTD	Defense Science and Technology Department
GPS	Global Positioning System
H <sub>2</sub>	Hydrogen
HICO	Hyperspectral Imager, Coastal Ocean
ISR	Intelligence, Surveillance, Reconnaissance
MEC	US Marine Corps Experimentation Center
MIW	Mine Warfare
MOE	Measure of Effectiveness
MOP	Measure of Performance
MODIS	Moderate Resolution Imaging Spectroradiometer
MRDC	Military Research and Development Center
MCSST	Multichannel Sea Surface Temperature
MUA	Military Utility Assessment
NAVOCEANO	Naval Oceanographic Office
NRL	Naval Research Laboratory
NSW	Naval Special Warfare
ONR	Office of Naval Research
QC	Quality Control
R&D	Research and Development
RF	Radio Frequency
RTArF	Royal Thai Armed Forces
RTN	Royal Thai Navy
S&T	Science and Technology
SST	Sea Surface Temperature
USPACOM	U.S. Pacific Command
UUV	Unmanned Underwater Vehicle
XBT	Expendable Bathythermograph
ZPBC	Zero Power Ballast Control

